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**A SUMMARY OF THE 1983
INTEGRATED FLYWHEEL TECHNOLOGY WORKSHOP**

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WORKSHOP OBJECTIVES

The use of flywheels to perform the functions of attitude control and/or energy storage on a variety of space missions has been of interest to NASA for several years. Preliminary studies were initiated in the early 1970's and have been carried forward by both government and industrial concerns ever since. Recent interest in this technology, on the part of NASA, resulted in the Integrated Flywheel Technology - 1983 Workshop held at the Goddard Space Flight Center in August 1983. This workshop had four primary objectives, shown in figure 1:

- 1) Determine the potential of flywheels for energy storage system applications as well as for combined energy storage and attitude control concepts.
- 2) Assess the state-of-the-art (SOA) in integrated flywheel technology through a review of government sponsored programs.
- 3) From this assessment, identify those technology areas which are in critical need of development to meet projected space mission requirements.
- 4) And finally, scope a program for the coordinated development of the required technology.

The results of this workshop are contained in NASA CP-2290 (ref. 1) and are summarized in this presentation.

- 0 DETERMINE POTENTIAL OF SYSTEM CONCEPTS
- 0 ASSESS SOA IN INTEGRATED FLYWHEEL SYSTEMS TECHNOLOGY
- 0 IDENTIFY CRITICAL TECHNOLOGY AREAS
- 0 SCOPE PROGRAM FOR COORDINATED ACTIVITY

Figure 1

PARTICIPATION

A total of 34 participants representing various government programs and interests attended the 1983 Integrated Flywheel Technology Workshop. The high level of interest in this technology within NASA is evident from the number of organizations represented at this conference (fig. 2). Presentations were made by many of the participants covering the disciplines of systems, power, and control. A compilation of those papers is contained in reference 1.

0 ORGANIZATIONS

- NASA HEADQUARTERS
- GODDARD SPACE FLIGHT CENTER
- JET PROPULSION LABORATORY
- JOHNSON SPACE CENTER
- LANGLEY RESEARCH CENTER
- LEWIS RESEARCH CENTER
- MARSHALL SPACE FLIGHT CENTER
- DEPARTMENT OF ENERGY

0 DISCIPLINES

- SYSTEMS
- POWER
- CONTROL

Figure 2

INTEGRATED SYSTEM CONCEPT

The system concept discussed during the workshop is depicted in figure 3. As can be seen, solar energy is converted to electricity by solar arrays during the sunlit portion of the orbit. This is used to power the spacecraft's subsystems, as well as to accelerate a rotating flywheel thereby storing energy for future use. During the occulted portion of the orbit, umbra power is obtained by decelerating the rotating wheel and converting the kinetic energy to electricity via a generator attached to the wheel shaft. This approach permits the elimination of the conventional battery storage system. In addition, functional integration with the vehicle's momentum control system can be effected, for example, by mounting these wheels on a set of gimbals.

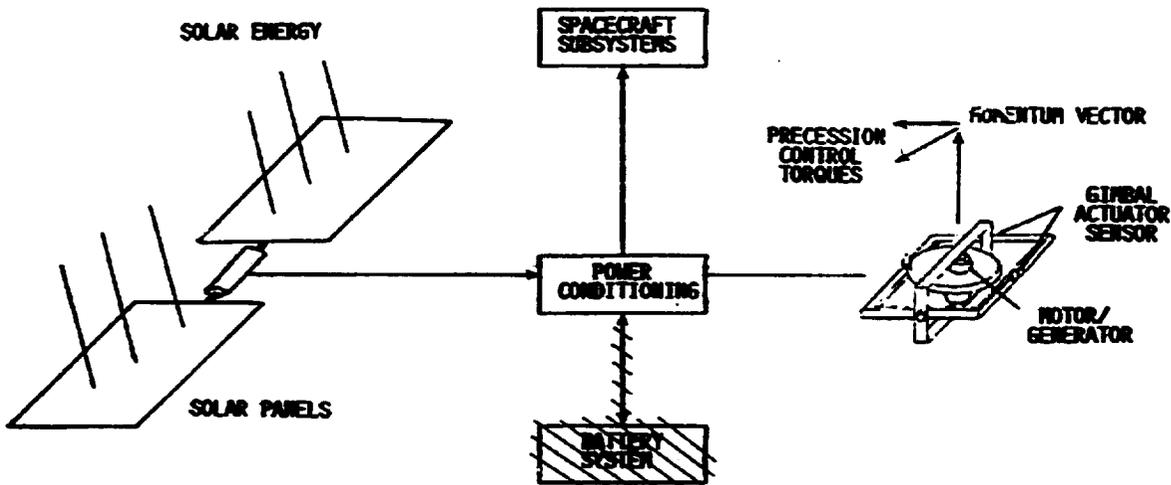


Figure 3

PRESENTATION TOPICS

The range of topics covered by the various presentations is shown in figure 4. These covered: system sizing and performance study results; information on state-of-the-art and advanced flywheel energy storage system concepts; a description of the DOE program on advanced composite material rotor developments; an overview of technology efforts abroad; data from system trade studies; a summary of advanced technology developments in electronics, rotor suspension and actuators; a definition of a technology program approach and of planned integrated system testing activities. A sample highlight of some of these topics is shown in the figures that follow.

- 0 SYSTEM SIZING TRADES AND PERFORMANCE STUDIES
- 0 ENERGY STORAGE SYSTEM CONCEPTUAL DESIGNS
- 0 FLYWHEEL PROTOTYPE DEVELOPMENTS FOR TERRESTRIAL APPLICATIONS
- 0 OVERVIEW OF EUROPEAN DEVELOPMENTS
- 0 POWER, ENERGY STORAGE, AND ATTITUDE CONTROL TRADE STUDIES
- 0 TECHNOLOGY ADVANCEMENTS IN ELECTRONICS, ROTOR SUSPENSION,
AND ACTUATORS
- 0 TECHNOLOGY PROGRAM OUTLINE
- 0 INTEGRATED SYSTEM TEST BED ACTIVITIES

Figure 4

MISSION APPLICATIONS STUDY

One of the system studies, performed in the early 1970's, was to examine the applicability of an integrated power/attitude control system (IPACS) concept over a broad range of mission types. The IPACS utilizes rotating flywheels to perform the dual functions of energy storage/power generation and attitude control. The types of missions examined during this study are listed in the table of figure 5. As can be noted, these selected missions encompassed small near-Earth satellites, geosynchronous satellites, interplanetary missions, and manned space stations. Power requirements ranged from a few hundred watts (180 W) to several kilowatts. Attitude control was specified at between 1 arcsecond and 1 degree. Results from that effort indicated that significant weight, volume, and cost savings could be realized by using the IPACS concept over the proposed conventional approach for all mission classes except the interplanetary flight (ref. 2)

	LAUNCH DATE	MISSION DURATION	MANNING	ORBIT CHARACTERISTICS (K/HR)	WEIGHT (LB)	POINTING ACCURACY (DEGREES)	POWER LEVEL (WATTS)	REMARKS
NEAR EARTH SATELLITE: EARTH OBSERVATIONS SATELLITE	1978	2 YRS	UNMANNED	SUN SYNCH 1100 (600)	770 (1700)	1.0	727w	EARTH OBSERV. SOLAR ARRAY/BATT
GEOSYNCHRONOUS SATELLITE: TRACKING & DATA RELAY SATELLITE	1977	3 YRS	UNMANNED	0° 35,700 (19,300)	1230 (2717)	0.9	300/180w	COMMUN. SAT. SOLAR ARRAY/BATT
PLANETARY SATELLITE: FARTHER-JUPITER/SATURN	1977	4 YRS	UNMANNED	30° 1.43 X 10 ⁸ (9.5 A.U.)	680 (1500)	0.05	350w	SCIENTIFIC SAT. ITS
SHUTTLE 30-DAY MISSION: EARTH OBSERVATION & COMMUNICATION TECHNOLOGY	1979	30 DAYS	MANNED	55° 500 (270)	37,500 (25,000)	0.5	3000w	EARTH RESOURCES FUEL CELL
MAN: ADVANCED SOLAR OBSERVATORY	1986	4-6 YRS	UNMANNED OPS. MANNED MAINTEN.	45 TO 55° 500 (270)	12,200 (27,000)	1 sec	500w	ASTRONOMY SOLAR ARRAY/BATT
ROBULAR SPACE STATION: NORTH AMERICAN DESIGN	1985	10 YRS	MANNED	55° 500 (270)	81,500 (180,000)	0.25	19,000w	GENERAL PURPOSE SOLAR ARRAY/ REGEN F/C

Figure 5

STATE-OF-THE-ART FLYWHEEL STORAGE UNIT

The encouraging results obtained from the previously mentioned study led to the design and fabrication of a flywheel storage unit. This device, shown in figure 6, is representative of the state of the art in homogeneous material flywheels. This unit is fabricated out of titanium, is suspended on conventional angular contact ball bearings, and is driven by two brushless d.c. motor/generators. Storage capacity of this unit at 35,000 rpm is about 1.5 kW-hrs. This device generates 2.5 kW of power at 52 volts d.c.. A detailed description of this unit can be found in reference 3.

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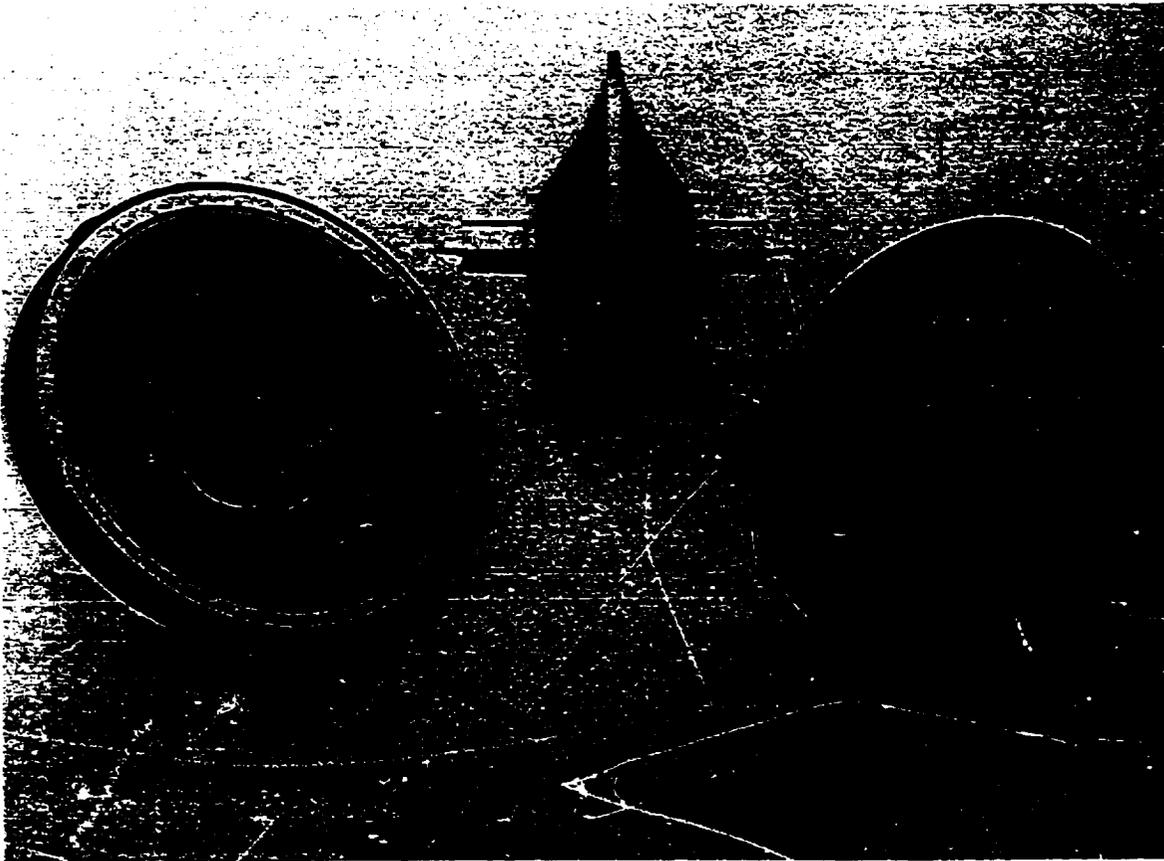


Figure 6

ADVANCED STORAGE UNIT CONCEPT

Capitalizing on significant advances in the state of the technology in composite materials and electromagnetics, several advanced storage system concepts have been postulated. Typical of such concepts is the unit shown in figure 7. This approach utilizes a pair of counter-rotating wheels to minimize the impact on the vehicle control system resulting from momentum variations incurred by the wheels during energy state changes. In addition to striving for higher energy density and safety through the use of composite materials, this concept proposes the use of magnetic bearings for lower system losses and thus higher efficiency and longer operational life. Additional efficiency and operational life gains are anticipated by employing permanent magnet brushless d.c. motor/generators. Details of this concept can be found in references 4-6.

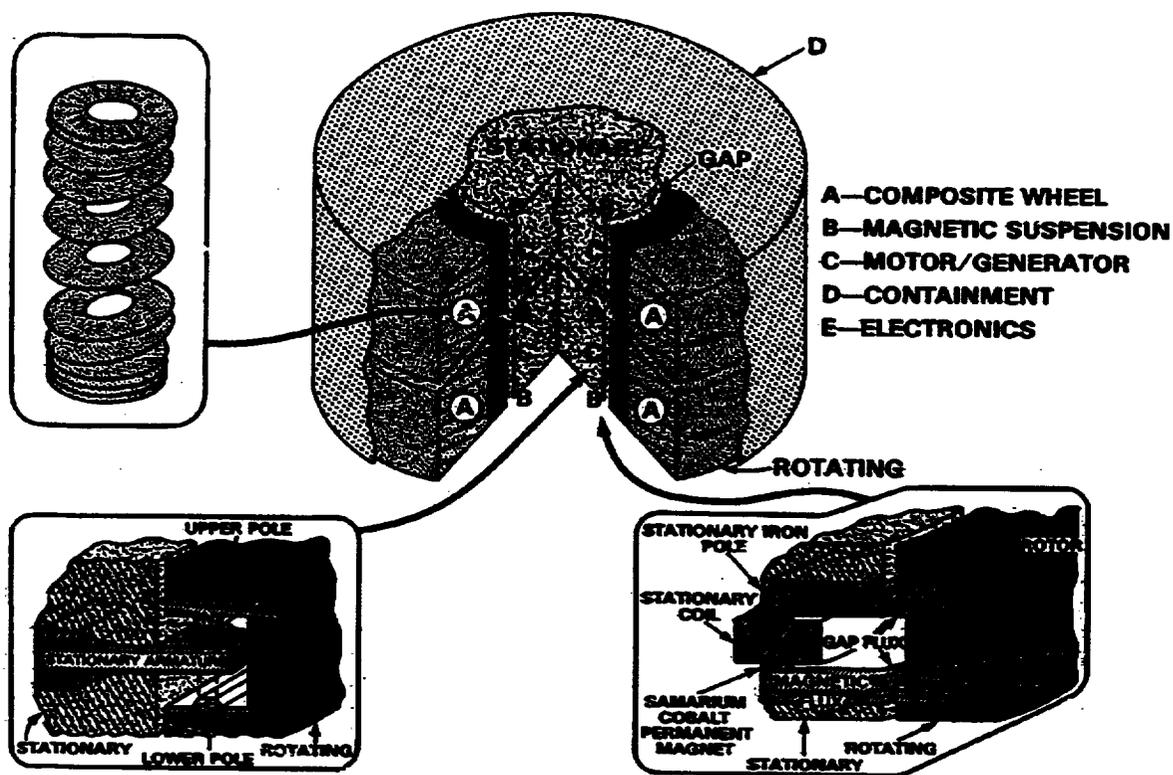


Figure 7

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FLYWHEEL MATERIALS

Composite materials applications to flywheels have, until very recently, been concentrated in the Department of Energy. Typical energy densities realized and postulated for flywheels using these materials are shown in figure 8. The benefits offered by composites over isotropic materials are quite evident in this figure. A summary of the DOE program can be found in reference 1, pages 35-46. In addition, advanced flywheels performance projections are given in reference 7.

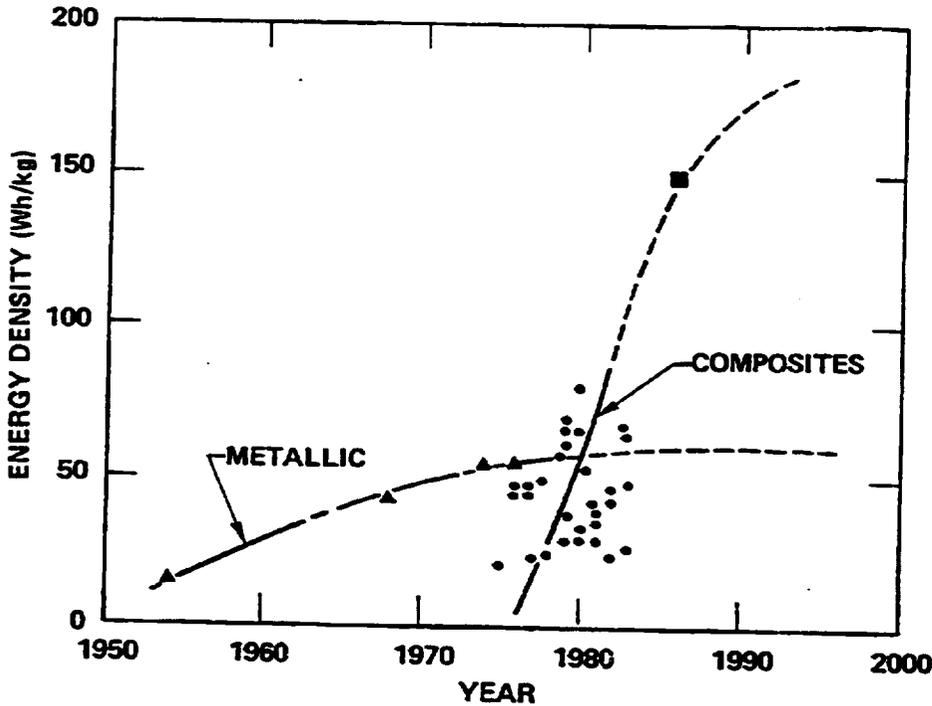


Figure 8

DOE FLYWHEEL CONCEPTS

In the course of the DOE program, several flywheel designs were generated. A number of these are shown in figure 9. The ten configurations depicted here represent three generic design categories, namely rims, disks, or rim/disk hybrids. Each of these concepts represents a significant advance in the application of composite materials to flywheel use.

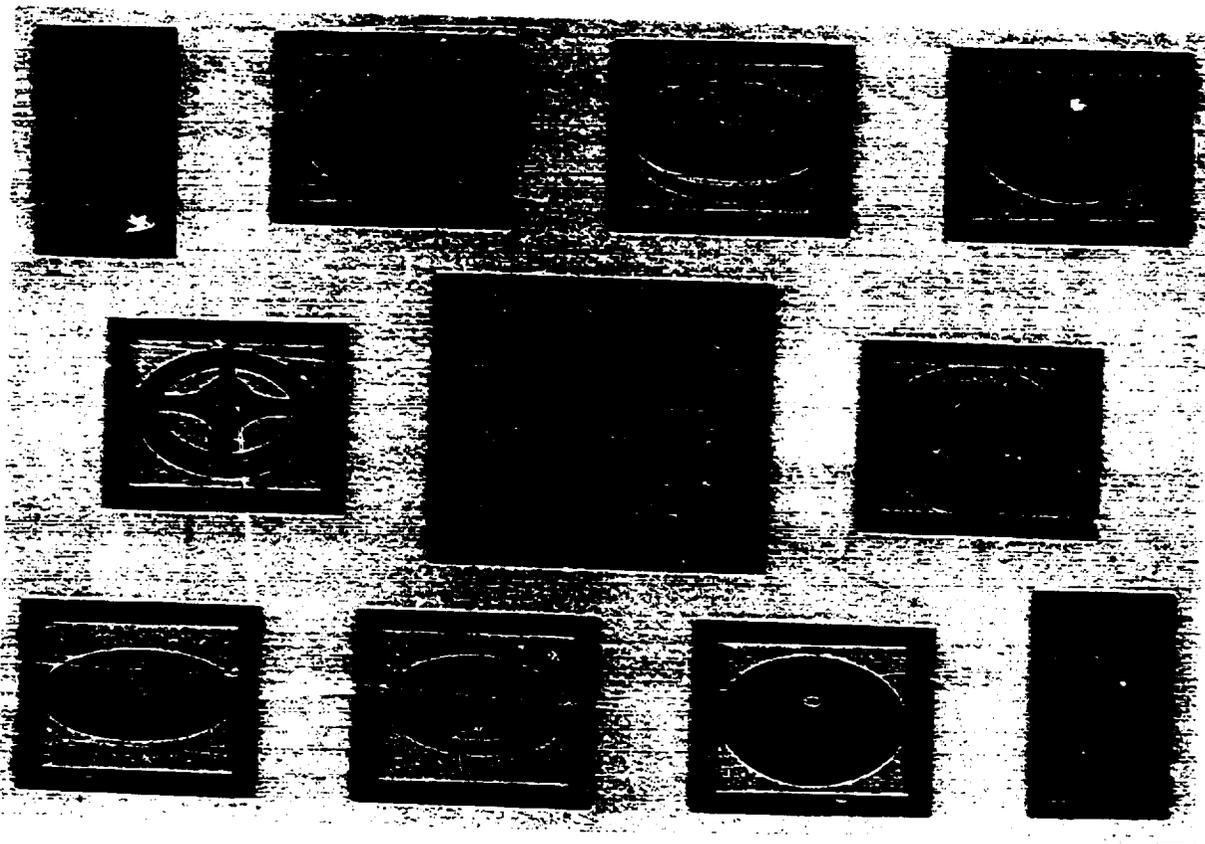


Figure 9

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SYSTEMS TRADE STUDIES

A typical example of a large variety of systems trade studies is demonstrated in figure 10. In this study, performed by R. Giudici of MSFC (ref. 1, pages 4^o-57), the weight to orbit of various energy storage/attitude control system concepts over the life of the intended mission is compared. As can readily be noted, flywheel systems do appear to be very competitive with other postulated concepts.

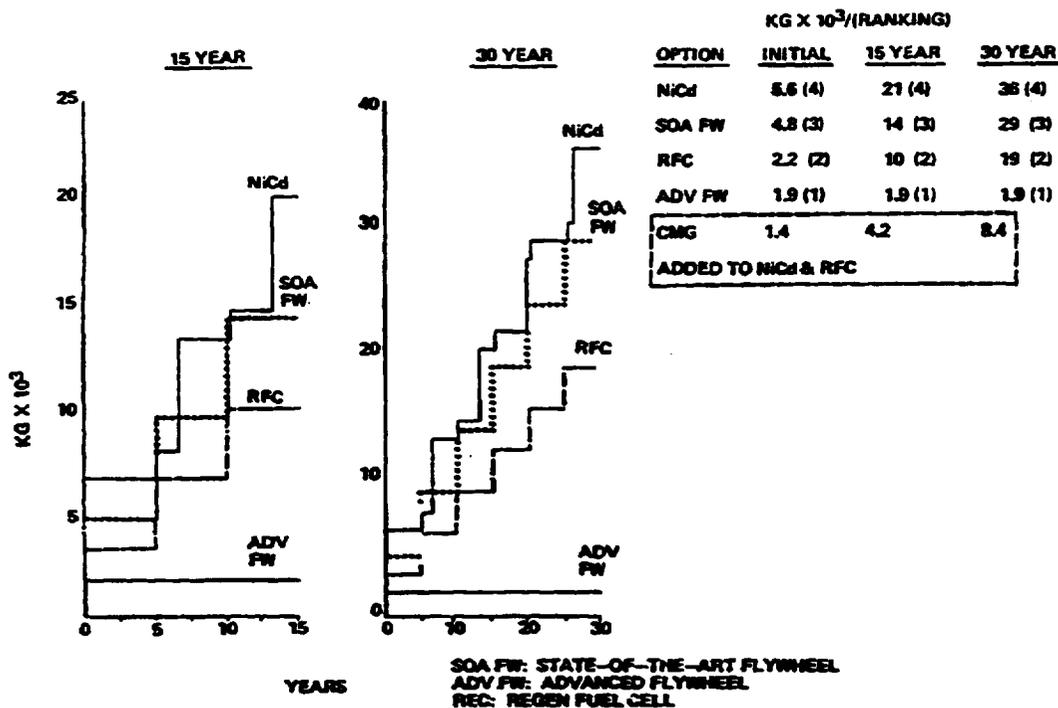


Figure 10

TECHNOLOGY ADVANCEMENTS

A recurring theme at the 1983 Integrated Flywheel Technology Workshop was the need for technology advanced in the areas of composite materials and their utilization, rotor suspension, and brushless d.c. motor/generators. Some steps have been taken in these areas and are contained in the Langley Research Center Annular Momentum Control Device (AMCD). This 5.5 ft. diameter graphite-epoxy ring is suspended on three magnetic bearing stations located around the rim, and is driven by a rim drive brushless d.c. motor (fig. 11). As can be noted, no contacting elements are used in this unit; therefore, significant efficiency and operational life gains can be achieved. Details of this concept and its applications can be found in references 8 and 9.

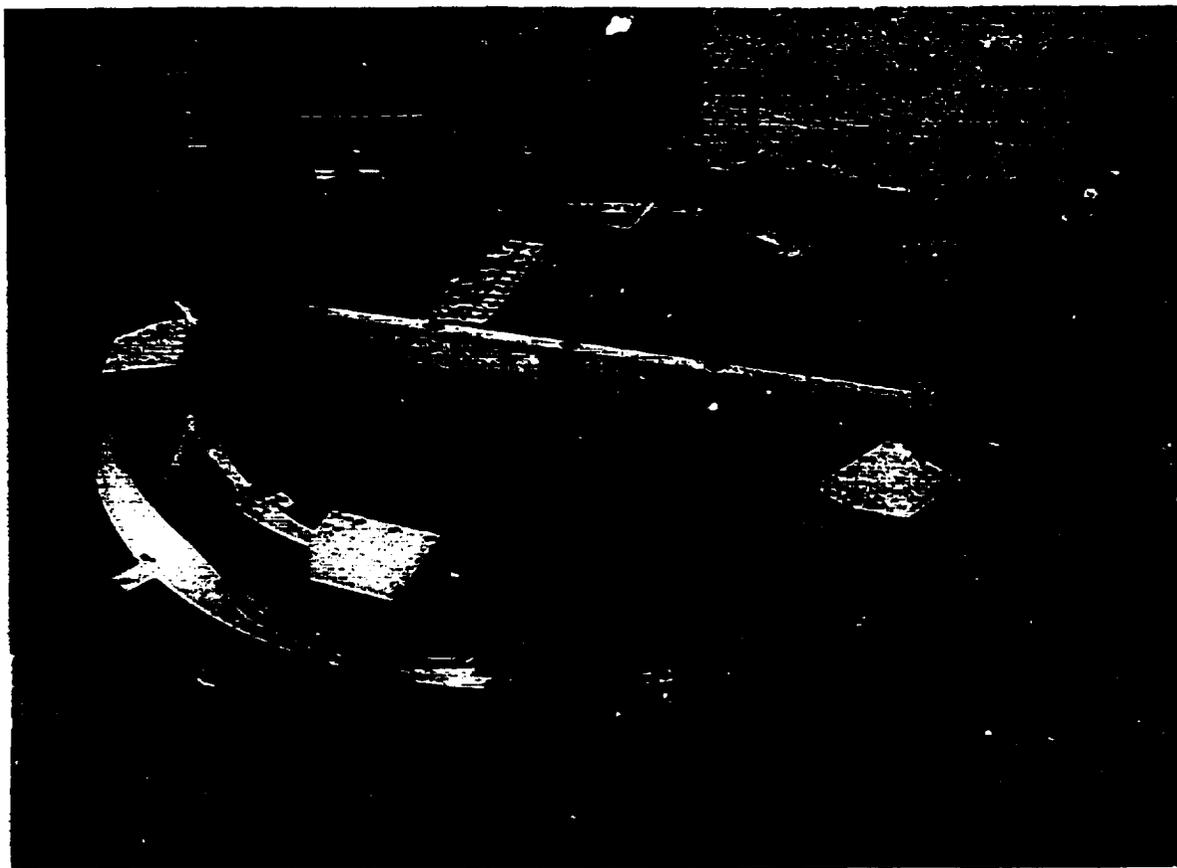


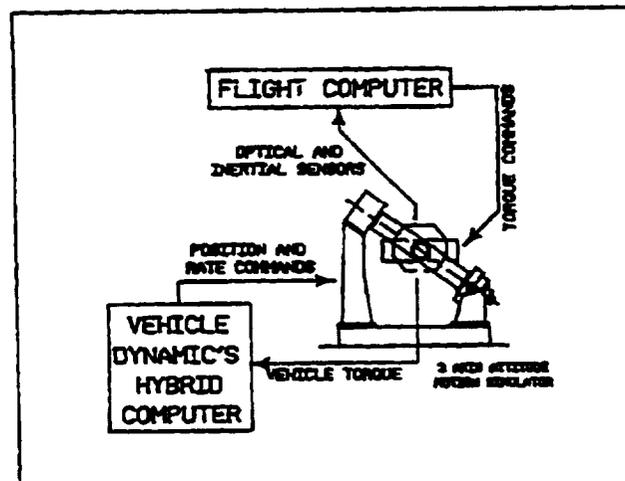
Figure 11

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INTEGRATED SYSTEM TESTING

An integral part of the technology evolution process is a thorough ground-based test program which may or may not be complemented by flight experimentation. In the case of the inertial energy storage system concept, testing on an attitude control system test bed, as well as a power system test-bed, simultaneously or separately, is being considered. Such a test-bed activity is described in figure 12.

SPACE STATION ATTITUDE CONTROL SYSTEM SIMULATOR



THE ATTITUDE CONTROL SYSTEM SIMULATOR CONSISTS OF:

- A LARGE 3 DEGREE OF FREEDOM TABLE POWERED BY HYDRAULIC ACTUATORS DESIGNED TO GIVE HIGH BANDWIDTH AND EXTREMELY FINE CONTROL THROUGH LARGE ANGLES
- COMPENSATION FOR EARTH ROTATIONAL RATE
- CONTROL MOMENT GYRO'S
- STAR TRACKER
- RATE GYRO'S
- STAR SIMULATOR AND SOLAR SIMULATOR PROVIDING COLLATED LIGHT IMAGING THE SPECTRAL CONTENT AND INTENSITY RECEIVED IN ORBIT

THE CONTROL SYSTEM SIMULATOR INCLUDES A 3 DEGREE OF FREEDOM POINTING MOUNT TABLE

- SEVERAL POSITIONS INSIDE POINTING MOUNTS
- POINTING MOUNT CONTROL WILL BE HOUSLY INTERACTIVE WITH SPACE STATION CORE CONTROL AND WITH THE DYNAMICS OF THE STRUCTURE

ATTITUDE CONTROL SYSTEM SIMULATION ACTIVITIES

- DEVELOPING A REAL TIME HYBRID SIMULATION OF THE SPACE STATION DYNAMICS AND THE ENVIRONMENT
- EVALUATION OF THE DYNAMIC CHARACTERISTICS OF THE ATTITUDE CONTROL SYSTEM AND THE NEW MOMENTUM MANAGEMENT CONTROL LAW
- EVALUATION OF FAULT ISOLATION AND REDUNDANCY MANAGEMENT TECHNIQUES
- EVALUATION OF MODIFIED AND IMPROVED COMPONENTS SUCH AS CMG'S AND RATE GYRO'S
- EVALUATION OF THE TRACE BETWEEN FIVE BODY POINTING, FIVE POINTING MOUNTS, AND FREE FLYERS
- INTEGRATION AND VERIFICATION OF INTERFACES BETWEEN CONTROL COMPONENTS AND SOFTWARE

Figure 12

TECHNOLOGY ISSUES

In addition to the technical discussions conducted at this workshop, a panel of experts, composed of one representative from each participating NASA field center, addressed the questions of critical technology, system integration, technology program justification and definition. The critical technology issues identified as a result of these efforts are shown in figure 13, and cover such areas as materials, rotor suspension, electromagnetics, electronics, systems integration, and safety.

0 MATERIALS

- ANALYSIS CAPABILITY OF MATERIAL PERFORMANCE
- OPTIMUM UTILIZATION OF MATERIAL PROPERTIES
- IMPACT OF ENVIRONMENT ON MATERIAL PROPERTIES

0 ROTOR SUSPENSION

- MAGNETIC BEARINGS (DYNAMIC CONTROL AND STABILITY)
- MECHANICAL BEARINGS (LUBRICATION. VIBRATION TRANSMISSION. MAINTENANCE. ON-LINE BALANCING ATTENDANT TO ON-ORBIT BEARING REPLACEMENT. REDUNDANCY)

0 POWER GENERATION

- MOTOR/GENERATOR DESIGN AND MATERIALS
- MOTOR/GENERATOR EFFICIENCY
- ELECTRONICS DESIGN AND EFFICIENCY
- POWER/VOLTAGE LEVELS AND BUS REGULATION

0 SYSTEMS

- INTEGRATION OF POWER AND CONTROL FUNCTIONS
- IMPACT OF INTEGRATION ON CONTROL LAWS AND ENERGY MANAGEMENT
- CONTINGENCY OPERATION FOLLOWING UNIT FAILURE
- MODULARITY AND/OR SCALABILITY
- SAFETY CONSIDERATIONS
- SYSTEM AND UNIT CHARACTERIZATION
- DATA BASE FOR SYSTEM AND COMPONENTS

Figure 13

WORKSHOP RECOMMENDATIONS

A major result arising from this workshop was that a general consensus was reached regarding the existence of strong support within the agency for integrated flywheel technology development, and that systems incorporating that technology have strong potential as an alternative energy storage approach for spacecraft applications. As such, the following recommendations (fig. 14) were made:

1) conduct a state of the technology workshop with industry, university, and government participation; 2) undertake a vigorous technology program to address and resolve all the technical issues raised during this conference; and finally, 3) adopt a lead center concept to insure a streamlined and coordinated technology program.

- **CONDUCT STATE OF TECHNOLOGY WORKSHOP (ASAP)**

 - INDUSTRY**

 - UNIVERSITY**

 - GOVERNMENT**

- **UNDERTAKE VIGOROUS TECHNOLOGY PROGRAM**

 - COMPOSITE MATERIALS AND FLYWHEELS**

 - MAGNETIC SUSPENSION**

 - M/G AND ELECTRONICS**

 - SYSTEM INTEGRATION AND OPERATIONS**

 - SYSTEM TRADES AND ANALYSES**

- **ADOPT LEAD CENTER CONCEPT**

 - COORDINATION OF HEADQUARTERS OFFICE GOALS
AND RESOURCES**

 - CAPITALIZING ON STRENGTHS OF PARTICIPATING
ORGANIZATIONS**

 - MINIMIZING DUPLICATIONS OF EFFORT AMONG AGENCIES**

Figure 14

REFERENCES

1. Keckler, C. R.; Rodriguez, G. E.; and Groom, N. J. (Editors): Integrated Flywheel Technology - 1983. NASA CP-2290, December 1983.
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